

Confusing the extragalactic neutrino flux limit with a neutrino propagation limit

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ABSTRACT: We study the possible suppression of the extragalactic neutrino flux due to a nonstandard interaction during its propagation. In particular, we study neutrino interaction with an ultra-light scalar field dark matter. It is shown that the extragalactic neutrino flux may be suppressed by such an interaction, leading to a new mechanism to reduce the ultra-high energy neutrino flux. We study both the cases of non-self-conjugate as well as self-conjugate dark matter. In the first case, the suppression is independent of the neutrino and dark matter masses. We conclude that care must be taken when explaining limits on the neutrino flux through source acceleration mechanisms only, since there could be other mechanisms for the reduction of the neutrino flux.

KEYWORDS: Neutrino, Dark Matter, Nonstandard Interaction, Cosmic Ray, Ultra-high Energy.

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1. Introduction

It is commonly believed that Ultra-high Energy (UHE) neutrinos should arrive at the Earth coming from very distant sources like Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB) following straight trajectories. Neutrinos interact only through weak interactions. They are not charged and if they have a nonzero magnetic moment it must be very small. Hence, there would be no interaction preventing them to travel cosmological distances [1]. The efforts to improve sensitivity to the UHE neutrino flux may test the existence of the Berezhinsky-Zatsepin (BZ) neutrinos [2]. Those neutrinos are generated through the same process that predicts the Greisen-Zatsepin-Kuzmin (GZK) cutoff [3] of Cosmic Ray (CR) flux, which has been observed by HiRes [4] and the Auger Observatory [5]. The most energetic CRs, most probably composed by protons and nuclei, may have an origin at relatively close sources, of the order of 100 Mpc for protons and even less for nuclei [6]. In fact, UHE CRs are most probably arriving from nearby AGNs [7]. But we observe that despite all the efforts to detect high energy extragalactic neutrinos, i.e., neutrinos with energies higher than 10^3 TeV, more and more restricted limits on their flux have been reported by several experiments due to the non observation of these neutrinos [8, 9, 10, 11, 12].

In addition, based on astronomical and cosmological observations, it is difficult to deny the existence of Dark Matter (DM) and Dark Energy (DE). Cosmological observations of clusters of galaxies indicate that the density fraction of DM is $\Omega_{\text{DM}} \approx 0.227 \pm$

0.014 [13]. The two most popular solution to the DM problem are *i*) a slight modification on the Newtonian dynamics [14] and *ii*) relic particles [15]. A DM relic particle candidate must be non-relativistic, must be stable on the cosmological time scale, and must interact weakly with other particles. Some of the possible candidates are: WIMPS [16], axions [17, 18, 19, 20, 21], MeV-scalar fields [22, 23], technicolor candidates [24, 25, 26], and ultra-light scalar fields [27, 28, 29, 30, 31, 32]. An ultra-light scalar field is motivated as DM because it can alleviate some of the problems that arise at galactic scale in the standard paradigm of cold DM, namely, the origin of cuspy halos [33] and the overproduction of substructure [34].

Neutrino interaction with DM, ν -DM for short, could have strong implications at cosmological scales. Interactions of neutrinos with light scalar fields have been studied with some interesting implications noticed, such as a reduction of the relic neutrino density, leading to a neutrinoless universe [35], or a modification on the CMB spectra [36, 37], or even a connection between the smallness of neutrino mass and a MeV-mass scalar field DM [38]. Furthermore, ν -DM interaction might affect the flux of UHE neutrinos. In particular, such interaction may suppress the neutrino flux resulting in a kind of GZK cutoff for neutrinos. Many DM candidates were analyzed in this context: heavy neutrinos as dark matter [39, 40, 41], lightest supersymmetric particles (LSP) discussed in Ref. [40] and updated in Ref. [42], and MeV-mass scalar field [22, 36, 38]. In all these cases the suppression is small, not interfering in the propagation of UHE neutrinos.

Nevertheless, we show here that a coupling between relic ultra-light scalar fields and neutrinos may imply a suppression of the UHE neutrino flux, in which case there may be a confusion between the flux limit at the source and a reduction of the UHE neutrino flux during propagation. Previous analysis have put constraints on the ν -DM interaction couplings for those models by using, for instance, SN1987A neutrino data or possible imprints on the angular power spectra of CMB anisotropies [36]. Nevertheless, those limits do not apply to our case, since they were obtained by assuming a mass of the scalar field $m_\phi > 10$ MeV while we will explore the possibility that ultra-light scalar field with $m_\phi \ll 1$ eV can couple to neutrinos. Such a small mass for the scalar particle gives a cross section with different behavior compared the one previously reported in other works [22, 23], allowing for new phenomena like a flux suppression for reasonable values of the coupling constants. Consequences of this type of ultra-light scalar fields have been studied in other astrophysical contexts like in the equilibrium of degenerate stars [43].

In this work we use the ν -DM coupling as described by the Feynman rule [23] shown in figure 1 where P_R denote the chiral projector, ϕ stands for the spin-0 dark matter field and $g_{\nu\phi}$ denote the strength of its Yukawa coupling.

In the next Section we show how the neutrino flux may vary due to a nonstandard interaction of neutrinos with DM. We also introduce the space of parameters, namely, cross section and DM mass, that lead to an important effect on the neutrino propagation through cosmological distances. In Section 3 we show the elastic scattering cross section for self and non-self-conjugate scalar fields while Section 4 is devoted to study the suppression to

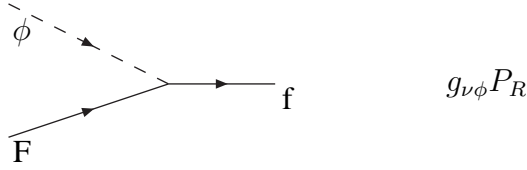


Figure 1: Feynman rule for the interaction of a neutrino with an ultra-light scalar field.

the neutrino flux due to the proposed ν -DM interaction. Finally in Section 5 we discuss our results and conclusions.

2. Neutrino flux and Dark Matter density

Once the neutrinos are produced at extragalactic sources, they have to propagate through distances of the order of 100-1000 Mpc to arrive at the Earth. For this scale of distances it is a good approximation to consider the distribution of sources and DM as homogeneous and isotropic. Then, considering ν -DM interaction, one can calculate the neutrino mean free path $\lambda = (n\sigma)^{-1}$, where n is the DM particle density ($\rho_{\text{DM}}/m_{\text{DM}}$) and σ is the ν -DM cross section. Therefore, at a distance L from the source the total flux expected is given by:

$$F(L) = F_0 e^{-L/\lambda}, \quad (2.1)$$

where F_0 is the flux when no interaction with the dark matter medium is considered. From Eq. (2.1) we learn that, e.g., a mean free path of approximately one third of the mean distance to the sources ($\lambda \sim L/3$) gives a 95% suppression of the initial flux. We do not show the result considering the evolution of sources because it does not change the result considerably and do not affect our conclusions.

Considering, for instance, $\lambda = L/3 \sim 33$ Mpc, we can compute the cross section σ as a function of the DM particle's mass m_{DM} . We consider for the mean DM density in the universe, $\rho_{\text{DM}} = 1.2 \times 10^{-6}$ GeV/cm³ [13]. In figure 2 we show the space of parameters that results in a 95% neutrino flux suppression or more.

We observe that there is a flux suppression even for a very small cross section provided that m_{DM} is also very small. So we may conclude that even very weakly interacting particles may have an effect on the neutrino flux if the mass of the background DM particle is extremely small, giving a high DM number density n .

Such an ultra-light particle has already been considered. DM scalar field candidates with mass in the range $10^{-22} - 10^{-24}$ eV have been proposed as viable DM particles [27, 28, 29, 30, 31, 32]. Even lighter scalar fields, with masses lower than 10^{-33} eV, have been postulated in order to explain DE [44, 45, 46, 47].

Concerning ultra-light scalar fields as DM, they have been studied for a number of self-interaction potentials, like quadratic ones [27]. The main idea behind these models is

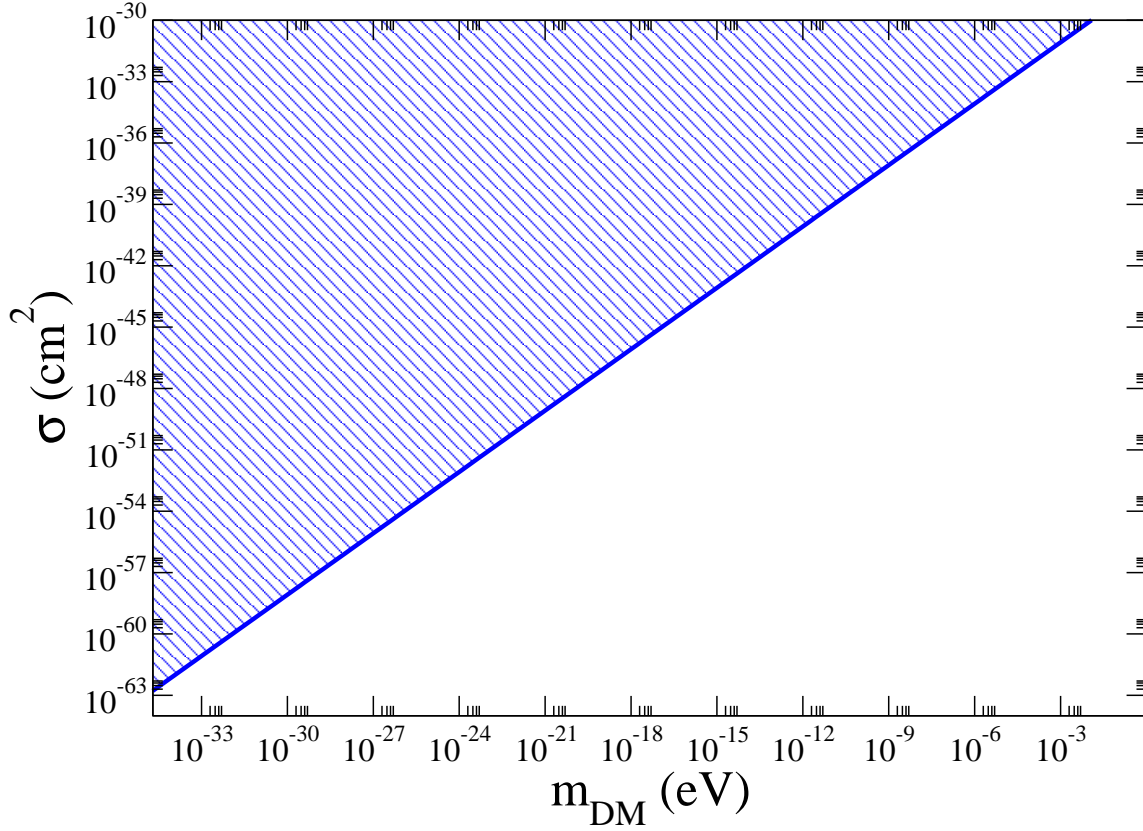


Figure 2: Neutrino cross section inducing a 95% neutrino flux suppression, as a function of the DM particle's mass m_{DM} . The shaded area shows the suppression parameters' space. We consider a density $\rho_{\text{DM}} = 1.2 \times 10^{-6} \text{ GeV/cm}^3$ and a mean source distance of $L = 100 \text{ Mpc}$.

that scalar fields were unified fields at a very early time after the origin of the universe. As the universe expands, the scalar fields cool together with the rest of the particles and finally they decouple from the rest of the matter. They condensate once they reach a critical temperature T_C . For the case of a complex scalar field the critical temperature is given by [48]

$$T_C = \sqrt{\frac{3q}{m_\phi}}, \quad (2.2)$$

where q is the charge density, defined as the excess of particles n over antiparticles \bar{n} , $q = n - \bar{n}$, and m_ϕ is the mass of the scalar field. From this formula one sees that an asymmetry of scalar particles, n , over antiparticles, \bar{n} , is required in order to have a high T_C . One can make an estimate [49] for the value of T_C considering $n \gg \bar{n}$, in which case the antiparticle contribution to the dark matter density is negligible and, therefore,

$$\rho_{\text{DM}} \simeq nm_\phi. \quad (2.3)$$

If we consider that the present dark matter density is $\rho_{\text{DM}} \simeq 0.23\rho_c$ and $\rho_c \simeq 4.19 \times 10^{-11} \text{ eV}^4$ we conclude that $n \simeq 10^{12} \text{ eV}^3$. For a scalar field mass of $m_\phi = 10^{-23} \text{ eV}$ we

get a critical temperature of condensation $T_c \simeq 10^{17}$ eV.

In this example, condensation occurs at very early stages of the evolution of the universe. After the scalar field condenses, most of these bosons lie in the ground state and one coherent field is appropriate to describe its evolution as the universe expands. It was shown in [50] that, for a coherent scalar field with a potential $V(\phi) \simeq \phi^k$, the energy density decreases as $\rho_\phi \sim a^{-6k/(k+2)}$, with a the cosmic scale factor. For our case of interest of scalar field DM [27], the potential is $V(\phi) \sim \phi^2$ and then, the energy density decreases as $\rho_\phi \sim a^{-3}$, i.e., it evolves as dust and hence as cold dark matter.

We show our results for two different situations: when the total amount of DM in the universe is composed of the ultra-light scalar field ($\rho_\phi = \rho_{\text{DM}}$) and for the case of a multi-component DM in the universe [29], where the ultra-light scalar field density is a ten percent fraction of the total density in the Λ CDM model. Therefore, in this case

$$n = 0.1 \frac{\rho_{\text{DM}}}{m_\phi}, \quad (2.4)$$

where m_ϕ is the scalar field mass and the ultra-light DM density is given by $\rho_\phi = 0.1\rho_{\text{DM}}$. Any other DM fraction can be obtained by simply rescaling the results.

3. The cross section

The kind of interaction we are assuming is the elastic scattering $\nu + \phi \rightarrow \nu + \phi$, where ϕ is the ultra-light scalar field. To compute an expression for the cross section in this process, we assume one of the models proposed in ref. [23], where the DM candidate can be either self-conjugate ($\phi = \phi^*$) or non-self-conjugate ($\phi \neq \phi^*$).

The Lagrangian for the interaction is given by

$$\mathcal{L} = g_{\nu\phi} \bar{\nu} \phi P_R F + H.c., \quad (3.1)$$

where $g_{\nu\phi}$ is the ν -DM coupling, P_R denotes the chiral projector $(1 + \gamma^5)/2$ and F denotes a new spin one half fermion that mediates the interaction.

3.1 Non-self-conjugate scalar field dark matter ($\phi \neq \phi^*$)

For this case, only the u -channel contributes to the cross section amplitude [23], and it is given by:

$$\sigma \simeq \frac{g_{\nu\phi}^4}{32\pi} \frac{s}{(u - M_I^2)^2}, \quad (3.2)$$

where the center of mass energy is $\sqrt{s} = \sqrt{2m_\phi E_\nu}$, E_ν is the neutrino energy, and M_I is the mass of the intermediate particle for the ν -DM interaction. Since we are considering an ultra-light scalar field, $u \ll M_I^2$ for all the considered energy range. In that limit the cross section can be written in the form:

$$\sigma \simeq \left(\frac{g_{\nu\phi}}{M_I} \right)^4 \frac{m_\phi E_\nu}{16\pi}. \quad (3.3)$$

3.2 Self-conjugate scalar field dark matter ($\phi = \phi^*$)

In this case there is a contribution from the s -channel [23]. Neglecting the neutrino mass, in the local limit approximation ($u, s \ll M_I^2$), both contributions from u and s channel cancel each other. But considering the neutrino mass the cross section, although small, is not exactly zero and it is given by the expression:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = & \frac{g_{\nu\phi}^4}{32\pi^2} \left[\frac{m_\nu^2}{4} \left(\frac{1 - \cos\theta}{(s - M_I^2)^2} + \frac{1 - \cos\theta}{(u - M_I^2)^2} \right) \right. \\ & + \left(\frac{1}{s - M_I^2} - \frac{1}{u - M_I^2} \right)^2 \left(\frac{s}{4}(1 + \cos\theta) - \frac{m_\phi^2}{4}(1 - \cos\theta) \right) \\ & + \left(\frac{1}{s - M_I^2} - \frac{1}{u - M_I^2} \right) m_\nu^2 \left(\frac{1 + \cos\theta}{2(s - M_I^2)} + \frac{1}{u - M_I^2} \right) \\ & \left. + \frac{2m_\nu^4}{s(u - M_I^2)(s - M_I^2)} \right]. \end{aligned} \quad (3.4)$$

In the limit where $s, u \ll M_I$ the cross section, after integration in solid angle, is reduced to

$$\sigma \simeq \left(\frac{g_{\nu\phi}}{M_I} \right)^4 \frac{m_\nu^2}{16\pi}. \quad (3.5)$$

In our computation of Eqs. (3.2) and (3.4) we consider, for simplicity, the limit $m_\nu^2 \ll s$, which for a neutrino energy of the order of $E_\nu \sim 10^{18}$ eV, and neutrino mass around 1 eV, translates into a restriction for the mass of the scalar field DM $m_\phi \gg \mathcal{O}(10^{-18})$ eV. We remark that, however, it is possible to consider smaller masses for the scalar field DM, recalculating the cross section without working in this limit.

4. Neutrino flux suppression

4.1 Non-self-conjugate scalar field dark matter

Remembering that $\lambda = (n\sigma)^{-1}$ and using Eq. (3.3) for σ , we have the neutrino mean free path given by

$$\begin{aligned} \lambda = & 16\pi \left(\frac{M_I/g_{\nu\phi}}{\text{GeV}} \right)^4 \left(\frac{\text{GeV}}{E_\nu} \right) \left(\frac{\text{GeV/cm}^3}{\rho_\phi} \right) \text{GeV}^2 \text{cm}^3 \\ \simeq & L_0 \left(\frac{M_I/g_{\nu\phi}}{\text{GeV}} \right)^4 \left(\frac{10^{18} \text{eV}}{E_\nu} \right) \left(\frac{\text{GeV/cm}^3}{\rho_\phi} \right), \end{aligned} \quad (4.1)$$

where $L_0 \simeq 42$ pc.

Depending specially on the ν -DM coupling strength, a neutrino flux suppression is possible. In this case, the non observation of UHE neutrino events by the experiments do

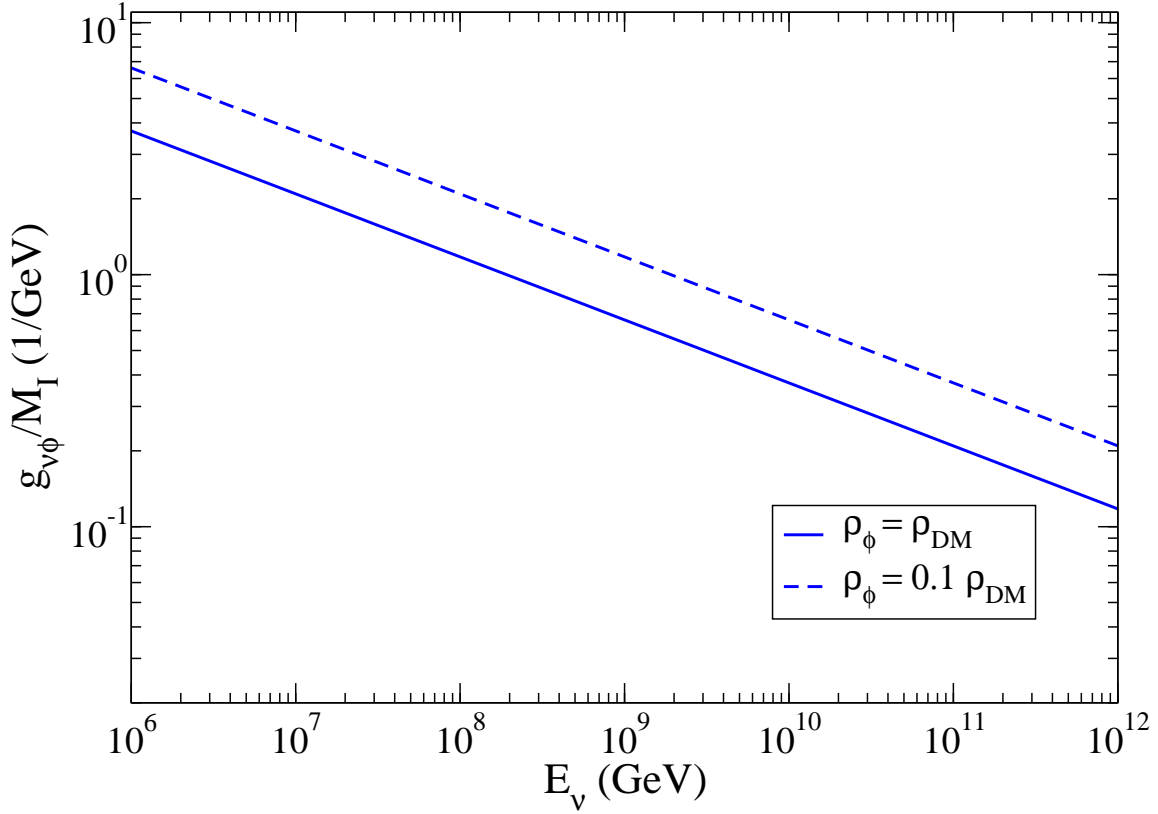


Figure 3: Ratio $\frac{g_{\nu\phi}}{M_I}$ as a function of the neutrino energy E_ν that induces a neutrino flux suppression, for the non-self-conjugate dark matter forming the total amount of DM (solid line) or a 10% fraction (dashed line). The regions above the curves predict stronger suppression. The considered mean distance to the sources is $L = 5 \times 10^2$ Mpc and the neutrino flux with no suppression is taken according to the MPR limit prediction.

not mean that there is a limit for the neutrino production in the extragalactic sources, but rather a reduction of the neutrino flux due to the ν -DM interaction. We can estimate the necessary strength of the coupling $g_{\nu\phi}$ to produce an important effect on the neutrino flux for propagation through distances of the order of 100 Mpc or more. It is also important to notice that, in this case, the mean free path is independent of the mass of the scalar field DM.

From Eqs. (2.1) and (4.1) we conclude that if the interaction have at least a strength given by the coupling

$$\frac{g_{\nu\phi}}{M_I} \gtrsim \left[\ln \left(\frac{F_0}{F} \right) \frac{L_0}{\rho_\phi E_\nu L} \right]^{\frac{1}{4}}, \quad (4.2)$$

the source flux limit is loose due to the above argument. In Eq. (4.2) L is given in Mpc, E_ν in GeV, ρ_ϕ in GeV/cm^3 , and M_I in GeV.

We show this result graphically in figure 3. Considering a non suppressed neutrino flux F_0 , equal to the one calculated by Mannheim, Protheroe, and Rachen (MPR) [51], we show in this figure the value of the ratio $\frac{g_{\nu\phi}}{M_I}$ that leads to a suppression giving a neutrino

flux, F , equal to the Waxman and Bahcall (WB) bound [52, 53]. The solid line is for a single ultra-light field forming the DM in the universe. The dashed one is for a 10% ultra-light DM component.

According to the WB bound, the maximum allowed neutrino flux is of the order of $\mathcal{O}(10^{-8})\varepsilon_Z \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, where ε_Z is of order unity and includes possible contribution of so far unobserved high redshift sources and the effect of redshift in neutrino energy. In this model protons are confined in the astrophysical sources and undergo photoproduction of mesons and neutrons. The mesons' decay generates the neutrino flux, while the neutrons escape from the acceleration site, decay, and produce the observed UHE cosmic rays.

On the other hand, the MPR flux model consider neutron optically thick sources ($\tau_{n\gamma} \gg 1$), i.e., in the photoproduction process neutrinos escape from the sources, but not the cosmic rays. Therefore, the relation between the neutrino and the cosmic ray fluxes is not direct and the neutrino flux limit is relaxed up to $\mathcal{O}(10^{-6}) \text{ GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. For these models it corresponds to a total neutrino flux ratio at the Earth of the order of $F_{\text{WB}}/F_{\text{MPR}} \approx \mathcal{O}(0.01)$, which is the ratio we use in Eqs. (4.2) and (4.4). For a recent discussion of the neutrino flux limits from various experiments see [54].

The value of L is fixed to be $L = 5 \times 10^2 \text{ Mpc}$. One can see that an ultra-light scalar field, if it exists as DM in the universe, may generate an extragalactic neutrino flux suppression effect. For instance, for a 10% scalar field DM component, if the ratio $\frac{g_{\nu\phi}}{M_I}$ is of the order 0.1, neutrinos with energies of the order of 10^{18} eV would present a suppression reducing the flux from the MPR to the WB value.

4.2 Self-conjugate scalar field dark matter

A similar analysis can be made for the cross section given in Eq. (3.5), valid for the case of self-conjugate scalar field dark matter. The resulting neutrino mean free path is

$$\begin{aligned} \lambda &= 16\pi \times 10^{-6} \left(\frac{M_I/g_{\nu\phi}}{\text{GeV}} \right)^4 \left(\frac{\text{eV}}{m_\nu} \right)^2 \left(\frac{\text{GeV/cm}^3}{\rho_\phi} \right) \left(\frac{m_\phi}{10^{-15}\text{eV}} \right) \text{GeV}^2\text{cm}^3 \\ &\simeq L_0 \left(\frac{M_I/g_{\nu\phi}}{\text{GeV}} \right)^4 \left(\frac{\text{eV}}{m_\nu} \right)^2 \left(\frac{\text{GeV/cm}^3}{\rho_\phi} \right) \left(\frac{m_\phi}{10^{-18}\text{eV}} \right), \end{aligned} \quad (4.3)$$

where $L_0 \simeq 42 \text{ pc}$. The required ratio $\frac{g_{\nu\phi}}{M_I}$ in order to have a reduction of the flux F_0 , with no suppression mechanism, to a flux F , or lower, due to the ν -DM interaction should be

$$\frac{g_{\nu\phi}}{M_I} \gtrsim \left[\ln \left(\frac{F_0}{F} \right) \frac{L_0 m_\phi}{\rho_\phi m_\nu^2 L} \right]^{\frac{1}{4}}. \quad (4.4)$$

The above ratio is shown in figure 4 as a function of the mass of the scalar field DM candidate, using $L = 5 \times 10^2 \text{ Mpc}$ and $m_\nu = 1 \text{ eV}$. We assume again F_0 equal to the MPR prediction, while the suppressed flux, F , is considered to be equal or below the WB limit.

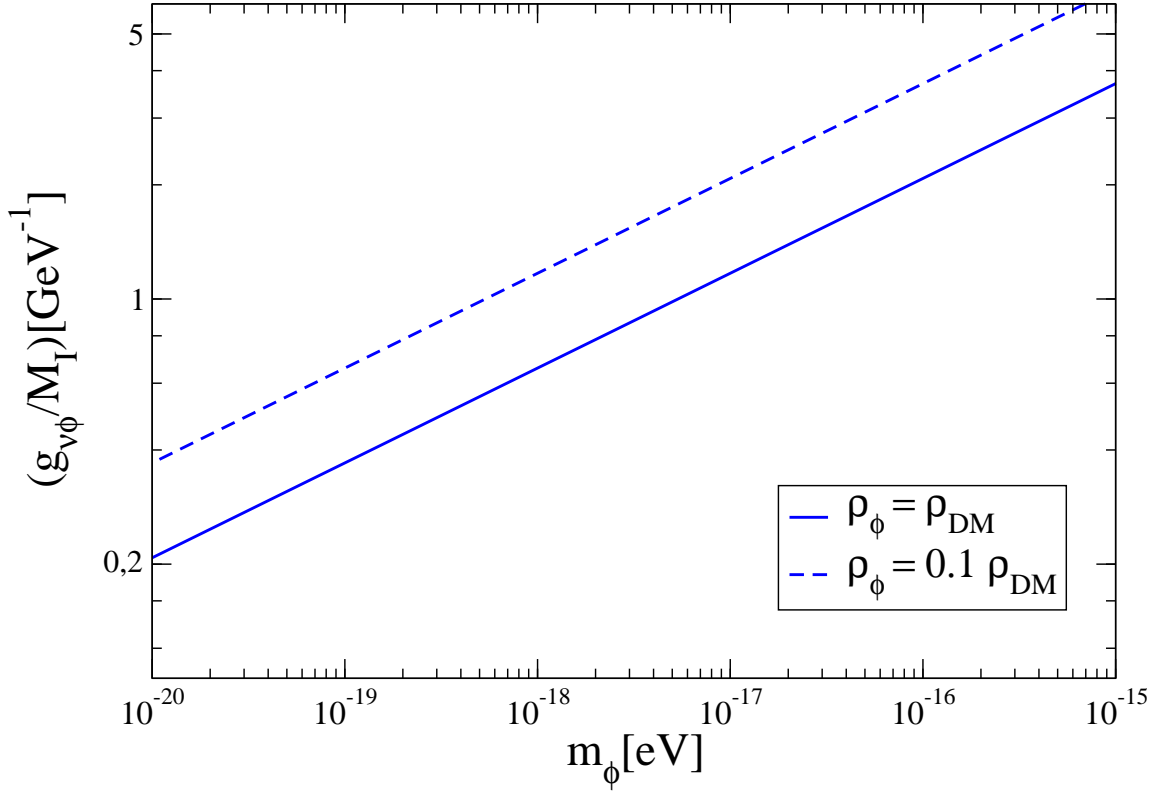


Figure 4: Ratio $\frac{g_{\nu\phi}}{M_I}$ as a function of the mass of the scalar field DM m_{ϕ} that induces a neutrino flux suppression (regions above the curves), for the self-conjugate dark matter forming the total amount of DM (solid line) or a 10% fraction (dashed line). We consider the mean distance to the sources $L = 5 \times 10^2$ Mpc, a neutrino mass of 1 eV, and the neutrino flux with no suppression is taken according to the MPR limit prediction.

The solid line is for a single ultra-light field forming the DM in the universe. The dashed one is for a 10% ultra-light DM component.

5. Discussion and Conclusion

There are several experiments, like IceCube and the Pierre Auger Observatory, expecting to detect extragalactic neutrinos. But neutrinos with energies above 10^{15} eV, coming from extragalactic sources, have not been detected yet. We study the possibility that UHE neutrinos could be absorbed while traveling from their sources to the Earth. In particular we illustrate this idea by considering an ultra-light particle as a component of the Dark Matter in the Universe.

We consider a mechanism for the neutrino interaction based on a scalar field dark matter model and we show that in this case the propagation of extragalactic neutrinos from sources 100 Mpc or farther from the Earth may be affected. This would give negative results on neutrino telescopes or UHE neutrino detectors. On the other hand, despite

neutrinos from a nearby supernova could interact with the DM halo around the collapsing star, the scale involved would not be sufficient for an absorption like the one proposed here.

Although nonstandard interactions of neutrinos with Dark Matter particles had been considered in the literature before, no important effect on neutrino propagation had been predicted. In most of the literature, light scalar field DM had been considered to be relativistic and the coupling to neutrinos was constrained due to measurable effects on the CMB spectra. In this work we have considered non-relativistic ultra-light scalar fields, proposed in the literature, that besides their gravitational effects, may not have other measurable astrophysical consequences.

To our knowledge, this is the first example of a possible suppression of the extragalactic neutrino flux due to propagation effects. Therefore, care must be taken when using the limits obtained by such experiments, since those limits can be due to two factors: source limit and/or absorption due to UHE neutrino-ultra light scalar field Dark Matter interaction during neutrino propagation from the source to the Earth. On the other hand, a positive signal of UHE neutrinos could be useful to put restrictions on models that contains a light scalar field DM candidate.

Similar arguments could be applied for particles other than neutrinos. For instance, in [20] it was analyzed the suppression of charged particles due to the interaction with a pseudoscalar and it was shown that the axion can play the role of a shield for high energy cosmic rays.

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